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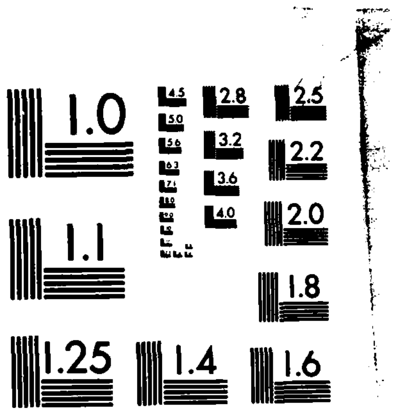
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SIMPLE K-ENERGY RADIATIVE SCALING LAW FOR IMPLODING WIRE ARRAYS AND GAS PUFFS

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1 March 1982

Technical Report

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A simple static K-energy radiation power scaling expression has been derived for element with $Z \leq 40$. Bound-Bound, Free-Bound, and Free-Free transitions have been included and accounted for in the expression. The results are shown to be in reasonable agreement with a wide range of experimental values.

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PREFACE

The authors would like to thank the members of the Plasma Radiation Branch at the Naval Research Laboratory for their kind assistance and warm hospitality on a number of visits to their institution.

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SECTION I

INTRODUCTION

The development of intense photon sources for nuclear weapons effects simulation has been actively supported by the Defense Nuclear Agency for at least the last twenty years. During this period it has become quite apparent that pulse power generators can be used successfully to heat material loads to the plasma state at temperatures and densities capable of exciting the K-shell of most low-Z elements. These subsequently radiate as intense X-ray sources. The material loads most often encountered with pulse power devices are: (1) an array of finely suspended wires, (2) a gas puff, and (3) a cylindrical annular foil. These material loads are rapidly vaporized by fast rising mega-ampere currents and, subsequently, converted to hot dense plasma that are copious emitters of intense X-rays. Because of the complexity of the phenomena involving radiation magnetohydrodynamics, it is not surprising that present day understanding of the plasma behavior leading to the emission of X-rays is still rudimentary. On the other hand, considerable progress has been made in understanding and modelling the radiative properties and energetics of low-Z and moderate-Z materials. Based on this understanding and on the empirical information regarding the temperature and density structure across the radiating plasma, it has appeared possible to derive a relationship which would show the manner in which the K-shell radiated power varies as a function of temperature, density, plasma size, and material (i.e., Z). This topic is the subject of this paper.

Before proceeding to the development of the actual scaling law, it is reasonable to review the application and importance of such work. Present results have generally established key features in the plasma structure of the majority of high K-shell yield experiments. The structure consists of a set of compressed hot spots or beaded spots, which appear to emit K-shell radiation. The spots are surrounded by an outer corona which predominantly radiates at a cooler temperature in the L-shell. This would be typical of aluminum, for example. The temperature structure suggests a distribution of ionization states across the plasma that reflects the core/corona pictorial representation and clearly indicates that not all of the plasma mass is heated to the K-shell. At higher power levels, it is also observed that more mass is heated to the K-shell level, but that substantially the same plasma structure is maintained. For higher Z loads, wherein K = > L-shell and L = >M-shell, we still note that the characteristic structure is preserved, i.e., core/corona. This result raises an important question about the behavior at higher power levels; namely, will higher power achieve higher temperatures or will it simply heat more of the plasma to existing or slightly higher temperatures. In the former case, the spectrum will be hardened, although the yields may not increase significantly above existing levels, while for the latter case the spectrum will be preserved but the yield will increase substantially. Since the goal of the program is to both harden the spectrum and increase the yields, it seems inevitable that a larger machine will have to be built in order to experimentally ascertain this information. However, from a theoretical point of view it should be possible to make some intelligent

comments regarding, at least, the scaling of the yield in terms of radiative properties of the load. To this purpose we derive a simple scaling law based on the radiative capacity of the plasma at temperatures capable of supporting K-shell radiation and where the size of the emitting region does not affect, significantly, the emitting qualities of the source. Reabsorption through the cooler regions has been neglected for simplicity.

SECTION II

THEORY AND RESULTS

Numerical simulations and spectroscopic analysis of wire or puff gas implosions suggest that the inner portion of the compressed plasma is hot enough to ignite the K-shell of all low-Z and some medium-Z elements. Estimates of the plasma density in the high temperature core region is on the order of 10^{19} to 10^{20} ions per cm^3 depending on whether the wires or puffs are used as the load material. Although these conditions are not those of a plasma in corona equilibrium, it is well known from the work of the Plasma Radiation Branch at the Naval Research Laboratory that for the K-shell emitting region of the plasma, a corona equilibrium analysis provides reasonably acceptable results for the radiated K-shell energy. Stretching this point a bit further, we will adopt the assumption of corona equilibrium for the core plasma and develop a simple scaling law for the radiated power in terms of temperature, density, and atomic number. Opacity effects will be completely ignored, but can be accounted for in a post hoc manner.

A survey of the literature (see, for example, the corona equilibrium calculations by Davis and Jacobs or D. Post) reveals that line radiation is dominant in hot plasmas up to about $Z = 40$. Beyond $Z = 40$, bremsstrahlung radiation begins to dominate the power spectrum. Detailed calculations in conjunction with the observations indicate that about 70% of the K-line yield emanates from the resonance levels of hydrogen-and helium-like ionization stages, on shots that are considered good in that they are of high yields. Using these empirical facts and the

assumption of corona ionization equilibrium, the peak K-line radiative power, K_L^M, associated with the resonance lines can be represented as

$$K_L^M \simeq N_e \sum_{q=1}^{2} N_q \, X(s \rightarrow q) \, \Delta E(s \rightarrow q) \tag{1}$$

where N_1, N_2 are N_{He}, N_H, respectively and $X(s \rightarrow 1) = X(1s^2 \rightarrow 1s2p)$, $X(s \rightarrow 2) = X(1s \rightarrow 2p)$ are the collisional excitation rate coefficients and $\Delta E(s \rightarrow q)$ is the excitation energy for the corresponding transitions, respectively. Finally, N_e is the electron density. At peak K-line emission the detailed calculations of Davis and Jacobs and Duston and Davis estimate that the fractional population densities are

$$N_1 \simeq 0.37 N_I \quad \text{and} \quad N_2 \simeq 0.5 N_I \,. \tag{2}$$

In addition $\Delta E(s \rightarrow 1) \simeq 0.95 \, \Delta E(s \rightarrow 2)$ where $\Delta E(s \rightarrow 2) = \frac{3}{4} I_H Z^2$. Hence

$$\Delta E(s \rightarrow 2) = 10 Z^2 \text{ in ev.} \tag{3}$$

Substituting these estimates into equation (1) yields

$$K_L^M \simeq 10 Z^3 N_I^2 \left[0.35 X(s \rightarrow 1) + 0.5 X(s \rightarrow 2) \right] \frac{\text{watts}}{\text{cm}^2} \tag{4}$$

where $N_e \doteq Z N_I$ has been used.

As a result of a number of calculations using the Coulomb-Born approximation, the Soviets have attempted to parametrize the electron impact excitation coefficient in the form (see Sobelman)

$$X \simeq 10^{-8} \left(\frac{I_H}{\Delta E} \frac{\chi_u}{\chi_\ell} \right)^{3/2} \frac{2}{g_\ell} A \frac{\beta^{1/2} (\beta + 1)}{\beta + \xi} e^{-\beta} \tag{5}$$

where χ_u (χ_ℓ) represents the upper (lower) state ionization energy, g_ℓ is the lower state statistical weight, $\beta = \Delta E/kT_e$, and $A \approx 20$ for $1s \rightarrow 2p$ transitions. This expression, equation (5), neglects exchange effects which can influence helium-like transitions by factors of two in some cases. Bearing this in mind and setting $\chi_{1s} = Z^2 I_H$, $\chi_{2p} = \frac{1}{4} Z^2 I_H$, and assuming $\beta >> \xi$ at $T_e = T_M$ yields

$$X^M(1s \rightarrow 2p) \approx 4 \times 10^{-8} \frac{1 + \beta}{Z^3 \beta^{1/2}} e^{-\beta} \text{ cm}^3/\text{sec}. \qquad (6)$$

A compilation of the NRL calculations is plotted in Figure 1 and suggests the following dependence:

$$T_M \approx 0.12 \; Z^{3.38} \qquad (7)$$

In addition, the β-dependence has been curve fitted for $Z \leq 42$ with the result

$$\beta^{-1/2}(1 + \beta) \; e^{-\beta} \simeq 0.012 \; Z^{5/4} \qquad (8)$$

Hence, the total power can now be written as

$$K_L^M \simeq 10^{-27} \; Z^{5/4} \; N_I^{\,2} \qquad (9)$$

where the knowledge that the resonance lines of the one- and two-electron systems account for roughly 70% of the radiated K-shell yield has been folded into equation (9). The result obtained from equation (9) is compared with the more detailed NRL models and as seen in Figure 2 is in reasonably good agreement, i.e., to within about a factor slightly less than two for $4 < Z < 60$.

The continuum contribution to the K-shell yield comes from the free-bound and free-free processes. In the case of the free-bound radiative recombination contribution,

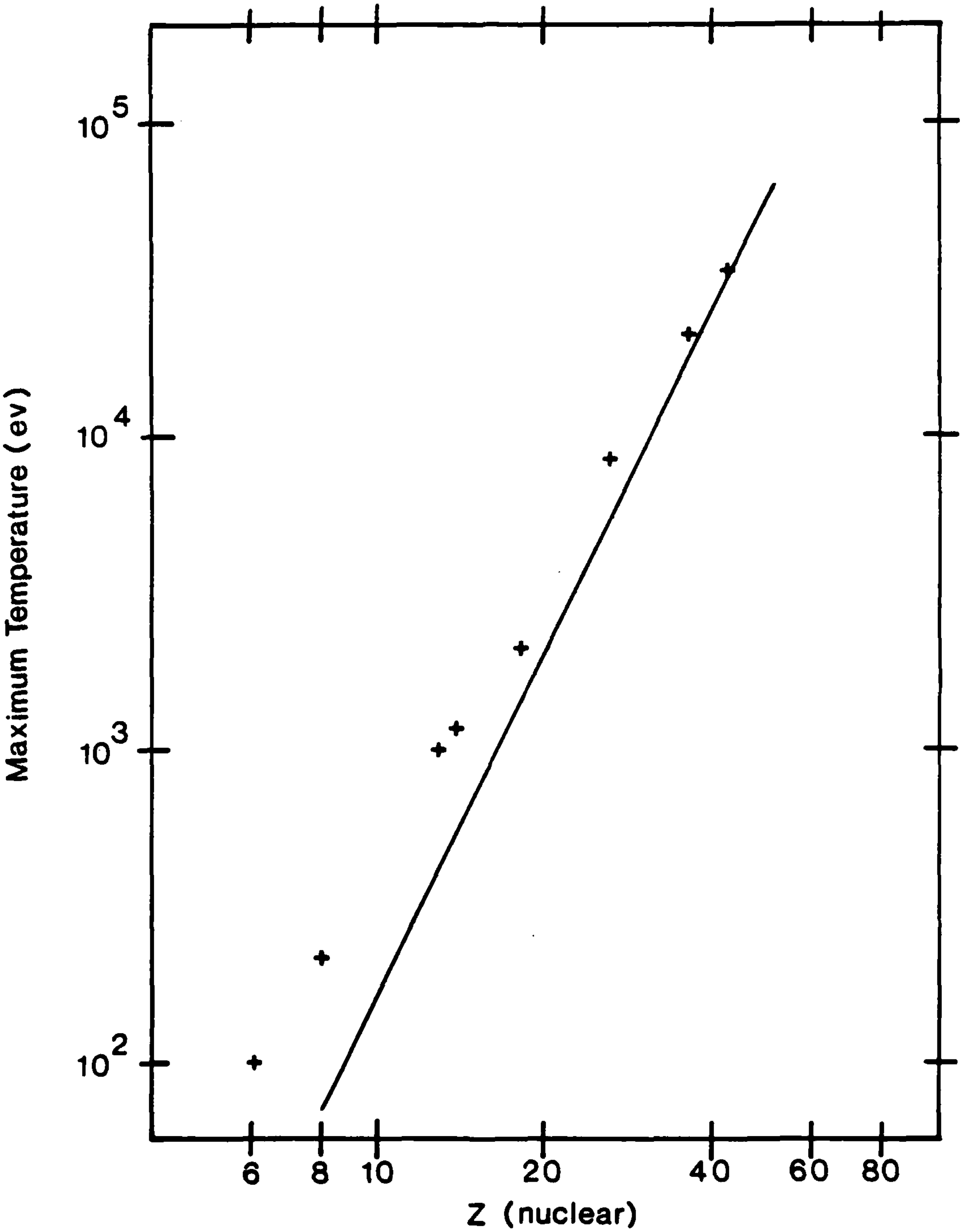

Figure 1. NRL Data Compared to Equation (7)

+ = NRL Data

—— = Equation (7)

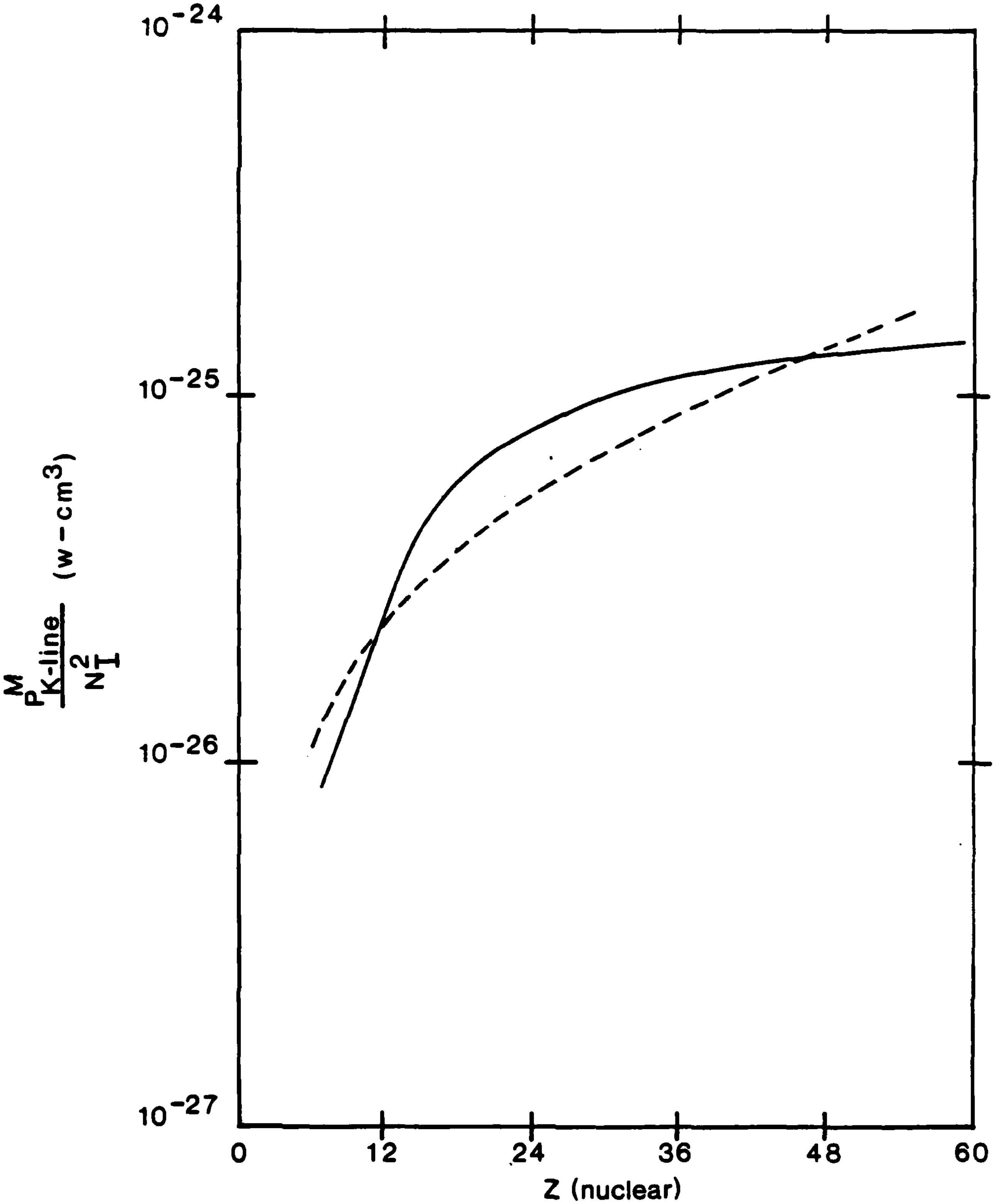

Figure 2. Model Calculations Compared to Equation (9)

—— = Model Calculations
- - - = Equation (9)

only two edges contribute to the K-line energies and can be represented by

$$K^M_{FB} \simeq 1.6 \times 10^{-19} N_e \sum_i \chi_i \alpha_i N_i \quad (10)$$

where χ is the ionization energy, α is the rate coefficient, and N_i is the recombining ion density. From a number of detailed calculations it can be shown that the following approximations are reasonable, namely

$$N_{\substack{\text{bare}\\ \text{Nucleus}}} \simeq 0.2\, N_H \quad \text{and} \quad 1.1\, \chi_{He} \simeq \chi_H = Z^2 I_H$$

If we take $\alpha = 5.2 \times 10^{-14}(Z/T_M)^{1/2}$ and substitute the above approximations into K^M_{b-f} we obtain

$$K^M_{b-f} \simeq 5 \times 10^{-32} Z^{4/3} N_I^{\,2} \quad (11)$$

The bremsstrahlung emission is given by

$$K^M_{ff} \simeq 1.5 \times 10^{-32} Z^3 N_I T_M^{-1/2} \int_{h\nu'}^{\infty} e^{-h\nu/T_M} d(h\nu)$$

where $h\nu'$ is the energy cutoff below which photons do not contribute to the K-shell and is set by the energy of the $1s^2 \rightarrow 1s\,2p$ edge. Hence

$$K^M_{ff} \simeq 5.3 \times 10^{-33} Z^{4.7} N_I^{\,2} e^{-h\nu/0.12\, Z^{3.38}} \quad (12)$$

Figure 3 shows a comparison between the total bremsstrahlung emission, i.e., $h\nu' = 0$ and that predicted from equation (12). The difference is about 40%.

The total power radiated at or above K-line energies is shown on Figure 4. The discrepancy between the two curves labeled "total emission" is due to inclusion of all

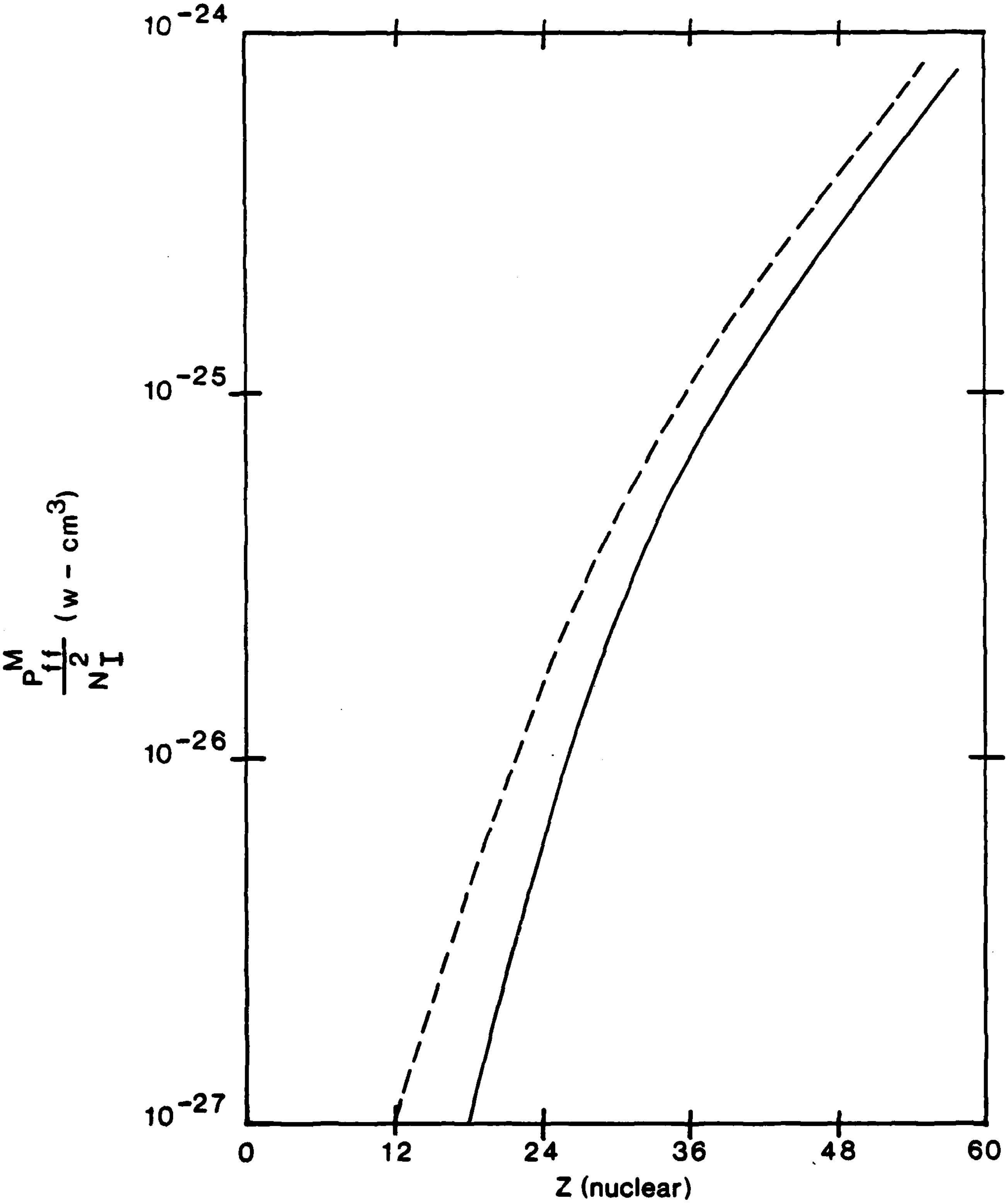

Figure 3. Total Bremsstrahlung Compared to Equation (12)

--- = Total
—— = Equation (12)

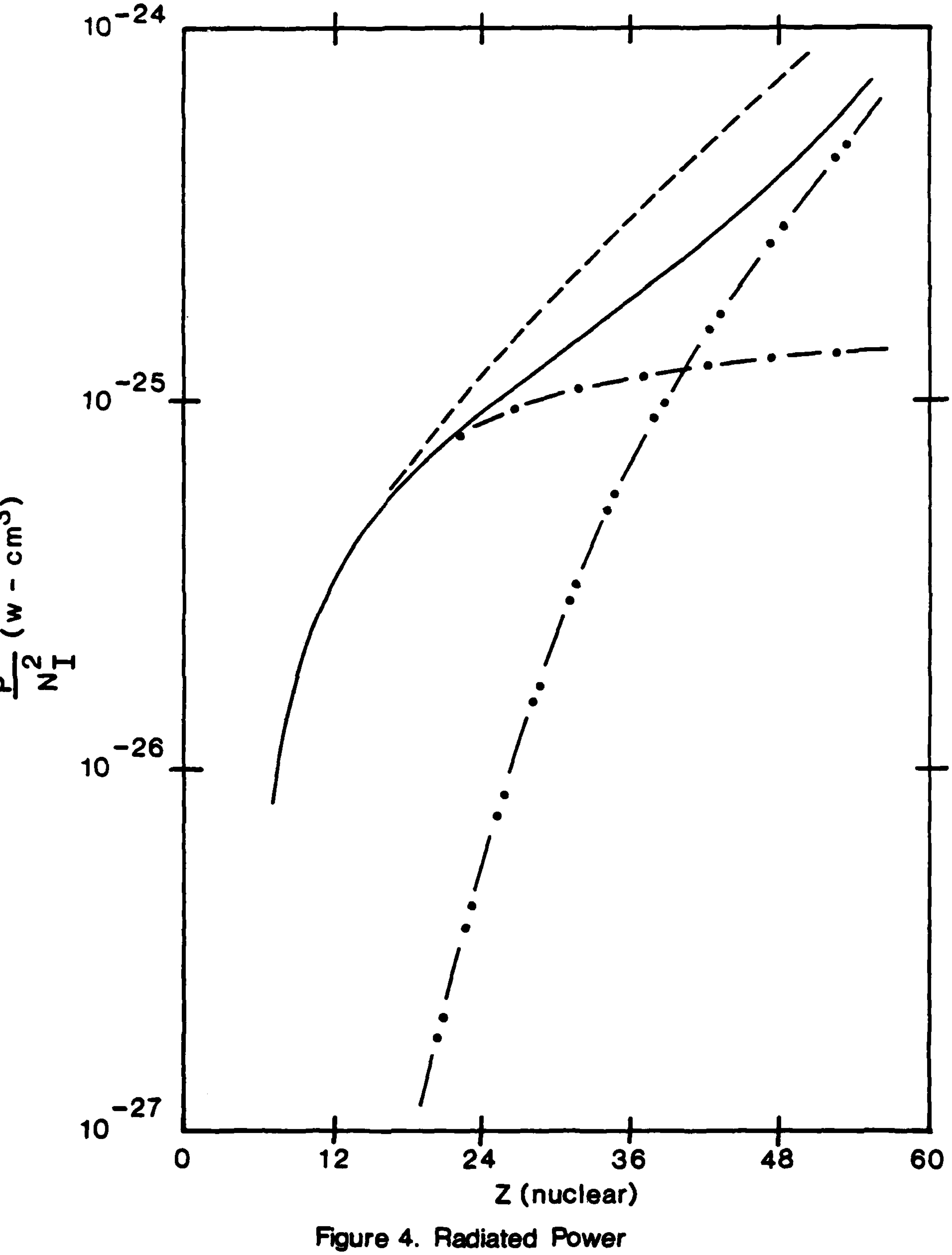

Figure 4. Radiated Power

- - - : Total (all energies)
—— : Total (above K-line)
- • - : K-line
-••- : Bremsstrahlung (above K-line)

energies in the free-bound and free-free estimates. Even so, the difference only amounts to about a factor of 2 at higher Z values.

The values obtained here are reasonable in comparison with some of the experimental values for a given Z. How-even, this simple scaling law should not be construed as anything other than what it is; a simple scaling law for estimating radiative yields. In the future, this model will be incorporated into a simple circuit-implosion model.

SECTION III

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